7th Int. Symp. "Nanostructures: Physics and Technology"
St Petersburg, Russia, June 14–18, 1999

QWR/QD.07

Temperature studies of single InP quantum dots

Valéry Zwiller, Mats-Erik Pistol, M. A. Odnoblyudov†‡ and Lars Samuelson
Solid State Physics, Lund University, Box 118, S-22100 Lund, Sweden
† Department of Theoretical Physics, Lund University, S-223 62, Lund, Sweden
‡ Ioffe Physico-Technical Institute, St Petersburg, Russia

In order to extract maximum information from photoluminescence studies of quantum dots, single dot studies have been performed. These studies do not suffer from fluctuations in the sizes of the dots or from variations in the environement of different quantum dots. We have performed experiments on single InP/GaInP quantum dots. The spectra always reveal several emission lines [1], no matter how much the excitation intensity is reduced, at least 4 or 5 irreducible lines are observed with an energy spacing of the order of 10 meV. The linewidth of the peaks is about 2 meV which is much larger than $k_B T$ at the experimental temperature of $T = 5$ K [1].

Information on the size and geometry of our self-assembled InP Quantum Dots grown on GaInP lattice matched to GaAs has been published elsewhere [2]. Atomic Force Microscopy (AFM) imaging of uncapped InP quantum dots shows a truncated pyramid shape with a characteristic elongation in the [110] direction [2, 3] (see Fig. 1), and is confirmed on capped samples by Transmission Electron Microscopy. AFM shows that most of the QDs are elongated in the [110] direction. The fully developped dots are typically 15 nm high and 60 by 40 nm at the base.

The sample was grown by Metal Organic Vapor Phase Epitaxy (MOVPE) at 580 °C. First, a 300 nm thick layer of GaInP was deposited on GaAs. The quantum dots were then produced by the deposition of 2.4 monolayers of InP, followed by a growth interupt of 12 seconds before the sample was capped by 300 nm of GaInP.

Experiments were performed to obtain the PL spectra of single quantum dots at various temperatures, from 5 K to 85 K. The sample was placed in a continuous flow helium cryostat. The average distance between the quantum dots was 10 microns which is more than the spatial resolution of the system (1 micron). In all measurements, the luminescence was collected using a 20x microscope objective. The excitation source was a frequency doubled Nd:YAG laser emitting at 532 nm. The emitted luminescence was dispersed by a 46 cm monochromator and was detected using a CCD camera, using typically 1 hour integration time. All the measurements presented here were made on single InP quantum

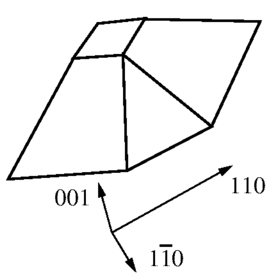

Fig. 1. Geometry of InP quantum dots. The dots are elongated in the [110] direction and have a typical height of 15 nm. The average base width is 40 nm and the average length is 55–65 nm.

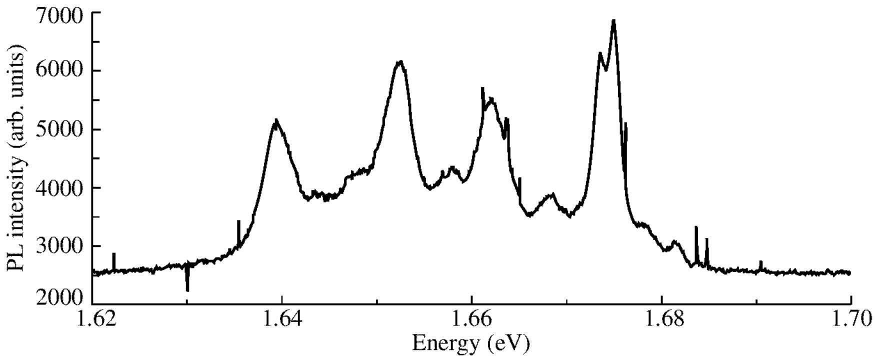

Fig. 2. A typical single dot spectrum, obtained at 5 K. Several peaks are visible, no matter how much the excitation intensity is reduced.

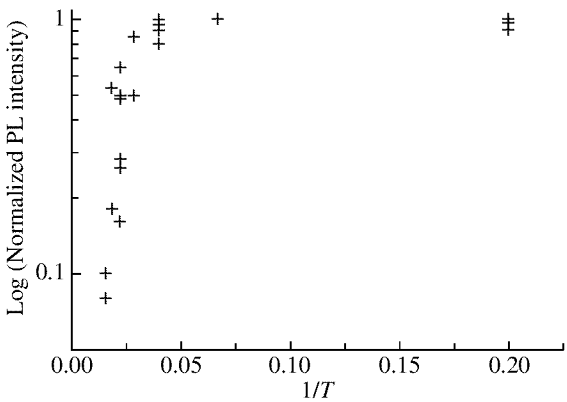

Fig. 3. Dependence of the photoluminescence emission intensity of a single InP quantum dot vs. temperature. Values were plotted for several emission lines.

dots. The excitation intensity was kept constant at about 0.1 W cm^{-2} while the temperature was increased in steps of 10 degrees.

Figure 2 shows a typical spectrum of an InP quantum dot obtained under low excitation intensity. The emission spans 40 meV and presents several peaks. With increasing temperature, all the lines are seen to decrease in intensity. This behavior has been observed to be the same in a dozen of dots.

Figure 3 is a plot of the intensity of different lines from different quantum dots measured at different temperatures. The log of the intensity is plotted against the inverse of the temperature. It is seen that all lines have a similar behavior and that an activation energy of about 1 meV can be deduced from these values.

Calculations of the energy levels for this type of quantum dots have been made, taking into account the strain and the piezoelectric field, using 6 bands **k.p** theory, within the envelope function approximation [4]. It was shown that the electrons are confined in the dot, while the holes states are localized at the base and at the top of the dot. The electron binding energy is about 210 meV [5] and the hole binding energy is about 120 meV. In the case of the valence band, the confinement is only due to strain[4]. In addition to these single particle binding energies, Coulomb attraction is expected to add a further 30 meV

to the exciton binding energy [6]. It can be expected that an increase in the temperature of the system will result in a decrease of the hole population, explaining the decrease of the photoluminescence intensity. However, the observed activation energy of temperature quenching would suggest a hole binding energy of about 1 meV, which is much lower than the binding energy due to the Coulomb attraction of the electron (i. e. assuming that the single-particle binding energy of the hole is zero). This shows that the activation energy is not due to thermal escape of the holes, and that some other mechanism is at work. Similar effects have been observed in quantum wells, and have been attributed to thermally activated non-radiative defects. This appears unlikely in this case since every dot would have to be associated with a defect. Possibly the interfaces, the edges or the corners of the dots may act as defects.

References

[1] D. Hessman, P. Castrillo, M.-E. Pistol, C. Pryor and L. Samuelson, *Appl. Phys. Lett.* **69**, 749 (1996).

[2] K. Georgsson, N. Carlsson, L. Samuelson, W. Seifert and L. R. Wallenberg, *Appl. Phys. Lett.* **67**, 2981-2 (1995).

[3] M.-E. Pistol, J.-O. Bovin, A. Carlsson, N. Carlsson, P. Castrillo, K. Georgsson, D. Hessman, T. Junno, L. Montelius, C. Persson, L. Samuelson, W. Seifert and L. R. Wallenberg, *23rd Int. Conf. on the Physics of Semiconductors* **2**, 1317-20 (1996).

[4] C. Pryor, M-E. Pistol and L. Samuelson, *Phys. Rev. B* **56**, 10404-10411 (1997).

[5] S. Anand, N. Carlsson, M.-E. Pistol, L. Samuelson and W. Seifert, *Appl. Phys. Lett.* **67**, 3016 (1995).

[6] C. Pryor, *Phys. Rev. B* **57**, 7190-7195 (1998).